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AN EMPIRICAL MODEL FOR LOADING RATIO EFFECT ON FATIGUE CRACK GROWTH RATE DATA

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Based on a limited amount of 72°F (22°C), positive loading ratio, constant amplitude loading fatigue crack growth rate test data generated for aluminum alloy 7010-T73651 a mathematical model of the data shift with loading-ratio was formulated. The mathematical model is only applicable to the Paris region of material behavior, and approximates the log-Paris coefficient as a linear relationship of the loading ratio,

(Continued on reverse side)

20. Abstract (Concluded)

Using the model a predictive Paris equation was formulated for an unexplored loading ratio prior to the generation of any data at this test-case loading ratio. Following generation of data at the test-case loading ratio and the calculation of the best fit Paris equation to the data set it was found to agree extremely well with the predictive equation formulated beforehand.

PREFACE

This interim technical report was submitted by the University of Dayton Research Institute, Dayton, Ohio, under Contract F33615-80-C-5011, "Quick Reaction Evaluation of Materials," with the Materials Laboratory of the Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio.

This effort was conducted during the period of May 1980 through February 1981. The author, Mr. Russell R. Cervay, would like to extend special recognition to Mr. Donald W. Woleslagle of the University of Dayton for painstaking care and diligent attention he demonstrated in generating the fatigue crack growth test data presented herein.

This report was submitted by the author in August 1981.

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BACKGROUND

A simple empirical mathematical model for constant amplitude loading fatigue crack growth rate (FCGR) test data is very useful for predicting the crack growth rate for a particular material at a condition where test data are nonexistent. In this manner the necessity for generating data at a particular unexamined test condition is circumvented. There are several such models already in existence that vary in their degree of complexity and their degree of success in predicting test data results.

Reference 1 presents constant amplitude loading FCGR test results for tests conducted at several different loading ratios (R-ratio = minimum load/maximum load), on two aluminum alloys, 7075-T6 and 2024-T3. That program considered and applied several different empirical mathematical models for the generated test data, one of them being the Paris equation:

$$da/dn = C\Delta K^{m} \tag{1}$$

where da/dn is the crack extension per load cycle and ΔK is the stress intensity range. The reference always used a fixed value for the Paris exponent, m, equal to 4.00 in fitting a Paris line to the data generated at the various loading ratios. The table presented in the above reference listing the Paris coefficients, C, for the lines fitted to the various R-ratio data sets is duplicated in Table 1 along with one additional column being added, the logarithm of the Paris coefficient, log C.

If R-ratio and log C listed in Table 1 are plotted on a linear set of axes, for both materials examined in the referenced effort, the points closely approximate straight lines (see Figure 1). The sole exception is the coefficient for the 7075 material with an R-ratio equal to or less than a value of zero.

TABLE 1

PARIS COEFFICIENT, C, FOR ALUMINUM ALLOYS
7075-T6 and 2024-T3
(Table Reproduced from Reference 1)

$$da/dn = C\Delta K^{4*}$$

Material	R	C	log C
7075-T6	≤0.00	5.52×10^{-21}	-20.26
	0.20	6.44×10^{-21}	-20.19
	0.33	1.00×10^{-20}	-20.00
	0.50	1.80×10^{-20}	-19.74
	0.70	3.95×10^{-20}	-19.40
	0.80	6.84×10^{-20}	-19.16
2024-T3	≤0.00	2.14×10^{-21}	-20.67
	0.33	5.40×10^{-21}	-20.27
	0.50	7.75×10^{-21}	-20.11
	0.70	1.24×10^{-20}	-19.91

* The crack growth rate, da/dn, is in terms of inches per cycle, while the stress intensity range, ΔK, is in terms of PSI $\sqrt{in}$.

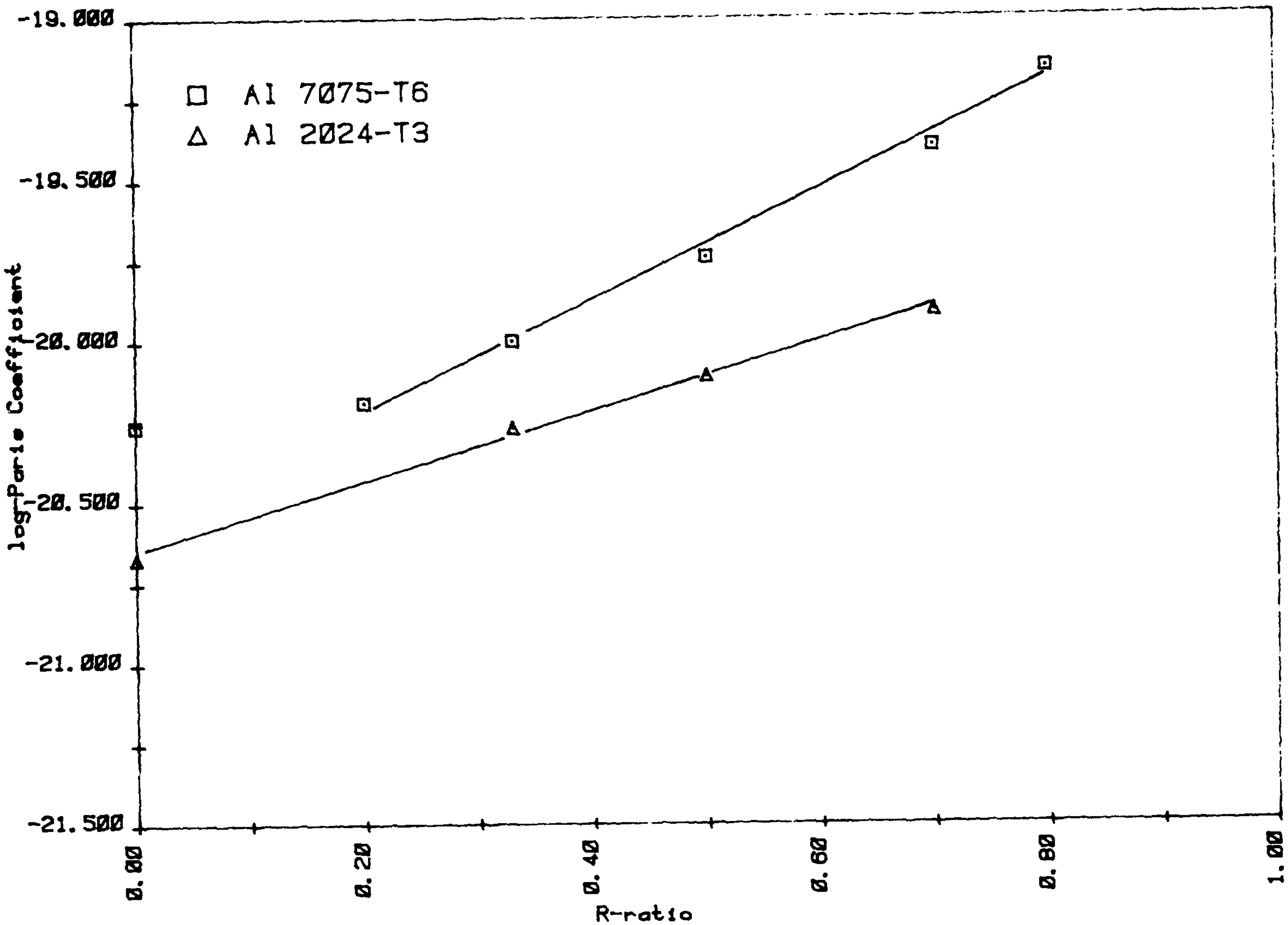


Figure 1. Reference 1 FCGR Test Data Loading Ratio Versus the Log Paris Coefficient.

SECTION II
INTRODUCTION

The empirical mathematical model for FCGR test data examined in this program is found in the Paris model; for that reason it can only be extended to the Paris data region, i.e., that portion of the test data where a straight line can fairly represent the FCGR data when it is plotted on a log-stress intensity range versus a log-crack growth rate set of axes. The threshold and the rapid crack velocity regions are not considered in this effort.

The mathematical model for room temperature FCGR test data discussed herein examines the variation of the Paris equation constants, exponent and coefficient, in response to varying loading ratio, R, using aluminum alloy 7010-T73651 plate material. The questions to be addressed in this program are: (1) If the exponent, m, is allowed to freely vary along with the coefficient, C, in determining the best-fit Paris straight line to a data set at various loading ratios, will a straight line still model a plot of loading ratio versus the log of the calculated Paris coefficients? and (2) If the answer to question (1) is yes, can the mathematical model be made more tractable by fitting a straight line to those same R-ratio data sets with the Paris exponent, m, fixed equal to the average value of the exponents derived in answering question (1)?

SECTION III
TEST MATERIAL

The test material was aluminum alloy 7010, which was provided in the T73651 overaged and cold-worked heat treatment. The 2-inch (50.8 mm) thick rolled plate was produced and furnished by Alcan Plate Limited, Birmingham, England. The material's chemical composition is very similar to Alcoa alloy 7050; the chemical compositions of the two alloys are presented in Table 2. Both alloys use Zr as the grain refiner rather than Cr which is more commonly used in other alloys. Both alloys (7010 and 7050) were developed for applications requiring high strength, high fracture toughness, exfoliation corrosion resistance, and stress corrosion cracking resistance in thick section product forms, e.g., 2 to 4 inch (50.8 to 101.6 mm) thick rolled plate. The test results of a more extensive mechanical property test program conducted on this particular plate is presented in Reference 2. One observation made during the FCGR testing portion of the referenced program was that test data for specimens with L-T or T-L grain orientations plotted in a narrow, well defined data scatter band. This characteristic was anticipated to be a valuable ally in formulating a simple mathematical model of the data based on a minimum number of completed tests.

TABLE 2

CHEMICAL COMPOSITION, WT. PERCENT

	Zn	Mg	Cu	Zr	Si	Fe	Ti	Mn	Cr	Other	Al
7010 Test Material	6.0	2.3	1.9	0.12	0.09	0.07	0.01	<0.01	<0.01	<0.01	Balance
Alcan 7010 Spec.	5.7-6.7	2.2-2.7	1.5-2.0	0.11-0.17	0.10 Max	0.15 Max	0.05 Max	0.03 Max	0.05 Max	0.03 0.15 tot.	Balance
7050 Mil Spec.	5.7-6.7	1.9-2.6	2.0-2.6	0.08-0.15	0.12 Max	0.15 Max	0.06 Max	0.10 Max	0.04 Max	0.05 0.15 tot.	Balance

The average tensile and fracture toughness properties for the piece of test material which were presented in Reference 2 are represented here in Tables 3 and 4.

TABLE 3

AVERAGE TENSILE PROPERTIES OF Al7010-T73651
All Tests Performed at 72°F (22°C)

Grain Orientation	Ultimate Strength KSI	Ultimate Strength (MPa)	0.2% Yield Strength KSI	0.2% Yield Strength (MPa)	Elongation (%)	% Reduction of Area
Longitudinal	73.7	(508)	64.4	(444)	12.9*	36.2
Long-Transverse	73.7	(508)	63.0	(434)	12.4*	33.2
Short-Transverse	73.4	(506)	65.0	(448)	7.9**	13.0

* Elongation in a 1 inch (25.4 mm) gage length.
** Elongation in a 0.5 inch (12.7 mm) gage length.

TABLE 4

AVERAGE FRACTURE TOUGHNESS TEST RESULTS FOR
ALUMINUM ALLOY 7010-T73651

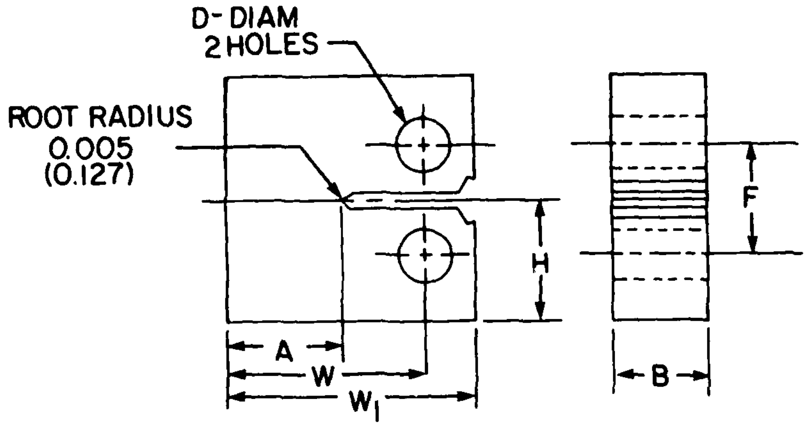
Test Orientation	Test Temperature °F	Test Temperature (°C)	K_Q KSI$\sqrt{in}$	K_Q (MPa$\sqrt{m}$)	ASTM Valid?
L-T	72	(22)	37.5	(41.2)	Yes
L-T	250	(121)	38.7	(42.6)	Yes
T-L	72	(22)	30.0	(33.0)	Yes
T-L	250	(121)	29.0	(31.9)	No
T-S	72	(22)	31.1	(34.2)	Yes
T-S	250	(121)	32.8	(36.0)	No
L-S	72	(22)	39.9	(43.9)	No
L-S	250	(121)	40.8	(44.8)	No
S-L	72	(22)	23.1	(25.4)	Yes

SECTION IV
TEST PROGRAM AND SPECIMENS

All of the FCGR tests discussed in this report were conducted in accordance with ASTM testing procedure E647-78T, "Constant-Load-Amplitude Fatigue Crack Growth Rates Above 10^{-8} m/cycle." All tests were completed in a room temperature laboratory air environment.

Tests were conducted at loading ratios, R, equal to 0.1, 0.3, 0.5, and 0.8. Based on these test results a predictive Paris equation was formulated for a loading ratio equal to 0.65 prior to generating test data at that loading ratio. The loading frequency for the data, previously presented in Reference 2, with a loading ratio equal to 0.1 was 20 Hz; all the remaining tests were conducted at 10 Hz. This was necessary in order to accurately maintain the application of a sinusoidal loading wave form to the smaller load train used in this effort.

The test data for a loading ratio equal to 0.1 was generated using the larger specimen configuration presented in Figure 2. All of the remaining test specimens were machined from failed open, large fracture toughness test specimens which were remanents of the Reference 2 program; using these small scraps as a source of test material necessitated using a smaller test specimen for this effort. The smaller CT specimen configuration in Figure 2 was used for all of the remaining loading ratios. All of the test data were generated using CT test specimens with L-T grain orientation.



DIMENSIONS INCHES (mm)

APPLICATION	A	B	W	W_1	H	D	F
R-RATIO = 0.10	.915 (23.2)	.300 (7.6)	1.500 (38.1)	1.875 (47.6)	.900 (22.9)	.375 (9.5)	.824 (20.9)
R-RATIO = 0.3, 0.5 0.65, 0.8	1.140 (29.0)	.200 (5.1)	1.400 (35.6)	1.750 (44.5)	.504 (12.8)	.375 (9.5)	.770 (19.6)

Figure 2. Compact Type Test Specimen Used in Generating Constant-Load-Amplitude FCGR Test Data.

SECTION V
RESULTS AND DISCUSSION

The constant amplitude loading fatigue crack growth test results for loading ratios equal to 0.1, 0.3, 0.5, and 0.8 are presented in Figures 3 through 6. The crack growth rate range that was considered for fitting the straight line was from 1.0×10^{-7} in./cycle (2.54 nm/cycle) to 1.0×10^{-4} in./cycle (2540 nm/cycle). For the remainder of the discussion the crack growth rates are in terms of inches per cycle, while the stress intensity range is in KSI$\sqrt{\text{in}}$. In determining the best fit Paris straight line, as illustrated in Figures 3 through 6, both the Paris exponent, m, and the Paris coefficient, C, were allowed to freely vary. The four Paris equations (2 through 5) representing each data set are presented below.

Loading Ratio	Paris Equation	
0.1	$da/dn = 6.46 \times 10^{-10}\ \Delta K^{3.74}$	(2)
0.3	$da/dn = 1.74 \times 10^{-9}\ \Delta K^{3.60}$	(3)
0.5	$da/dn = 2.67 \times 10^{-9}\ \Delta K^{3.67}$	(4)
0.8	$da/dn = 7.18 \times 10^{-9}\ \Delta K^{3.70}$	(5)

The log-Paris coefficient, log C, for the four data sets are plotted in Figure 7 as a function of loading ratio, R. The four points are distributed around a straight line defined by equation (6).

$$\log C = 1.438R - 9.277 \qquad (6)$$

If the logarithm of both sides of the Paris equation (1) is taken it becomes equation (7).

$$da/dn = C\Delta K^{m} \qquad (1)$$

$$\log da/dn = \log C + m \log \Delta K \qquad (7)$$

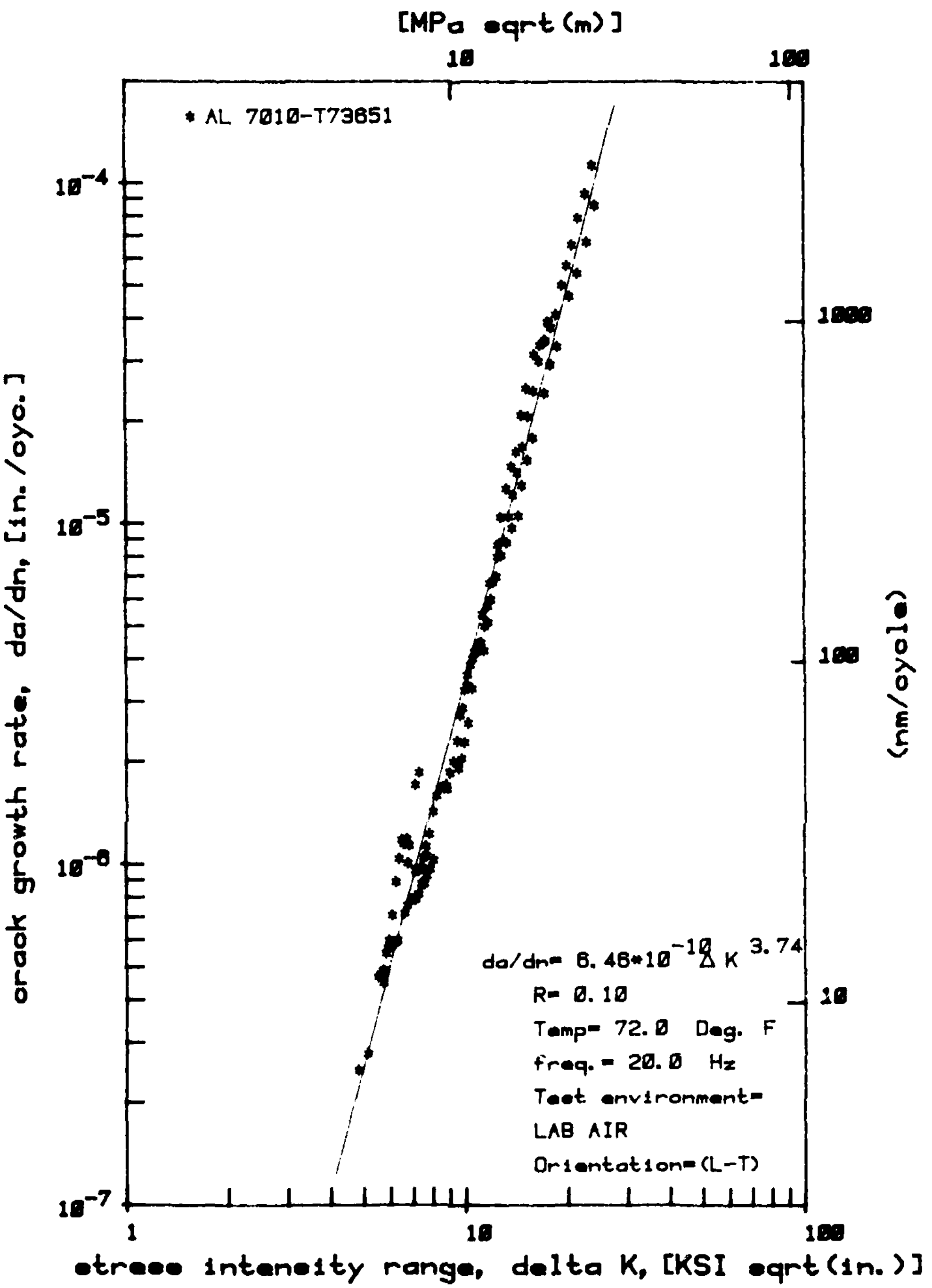


Figure 3. Room Temperature, Loading Ratio = 0.10 FCGR Test Data for Al 7010-T73651.

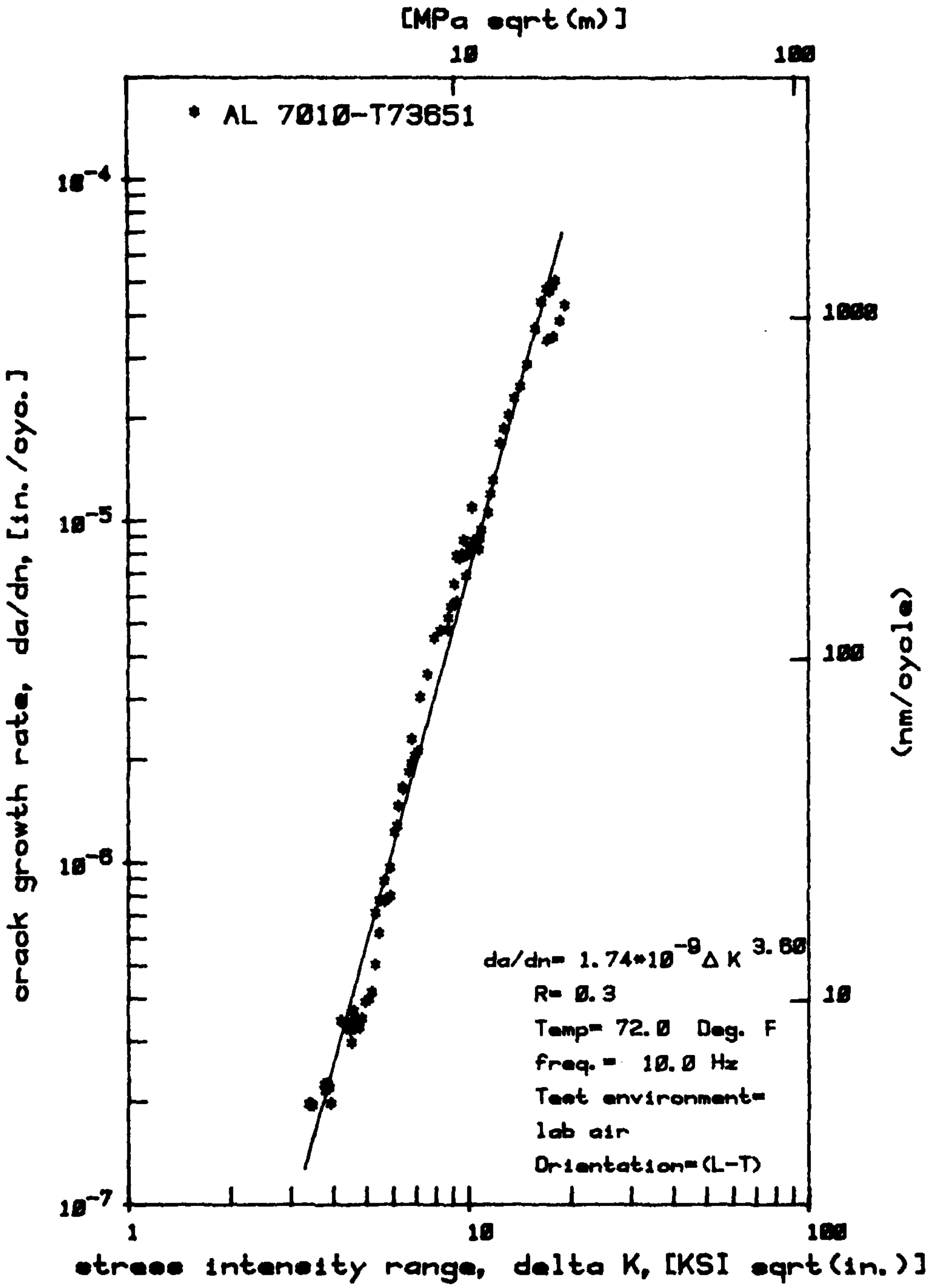


Figure 4. Room Temperature, Loading Ratio = 0.30, FCGR Test Data for Al 7010-T73651.

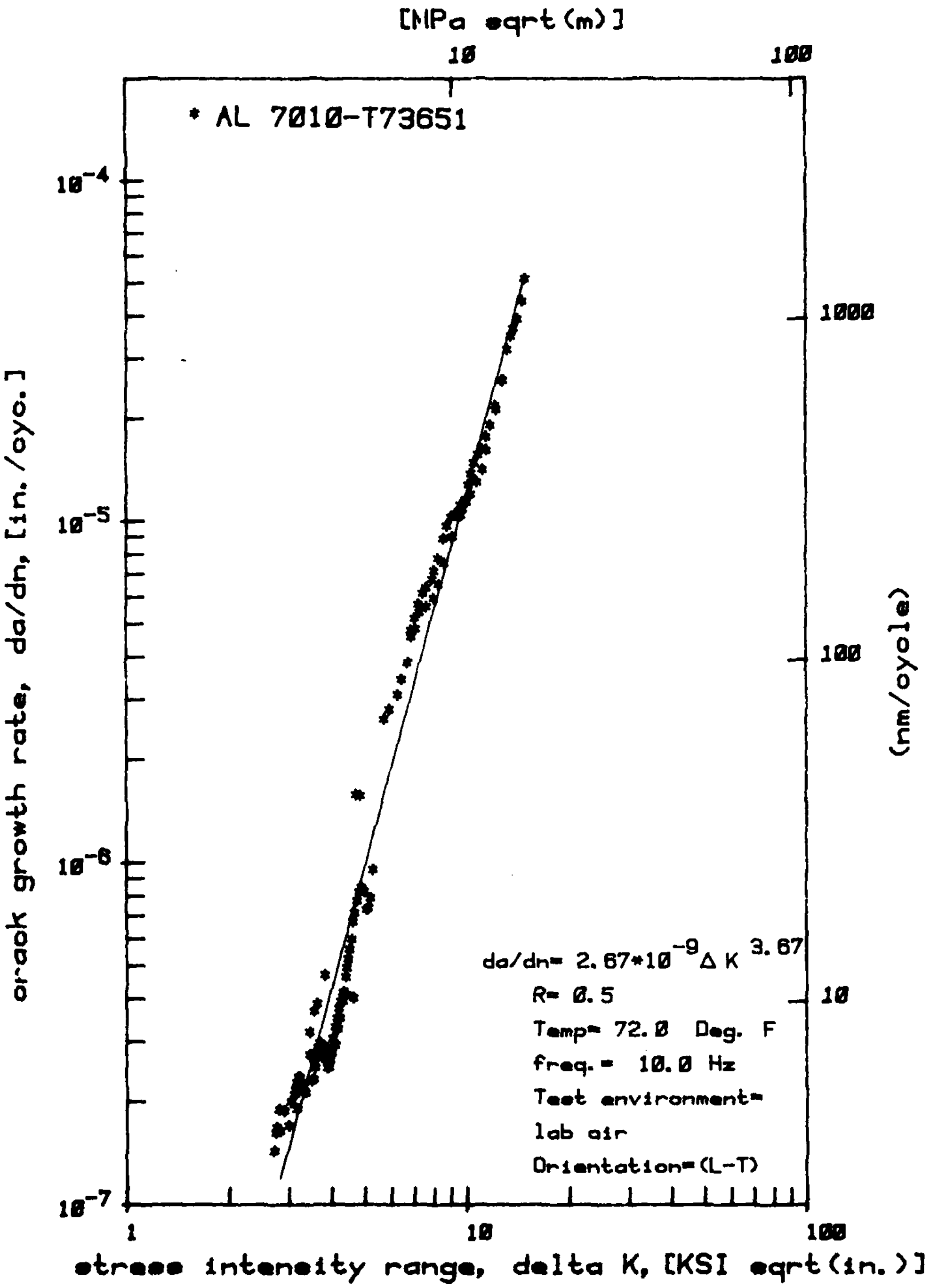


Figure 5. Room Temperature, Loading Ratio = 0.5 FCGR Test Data for Al 7010-T73651.

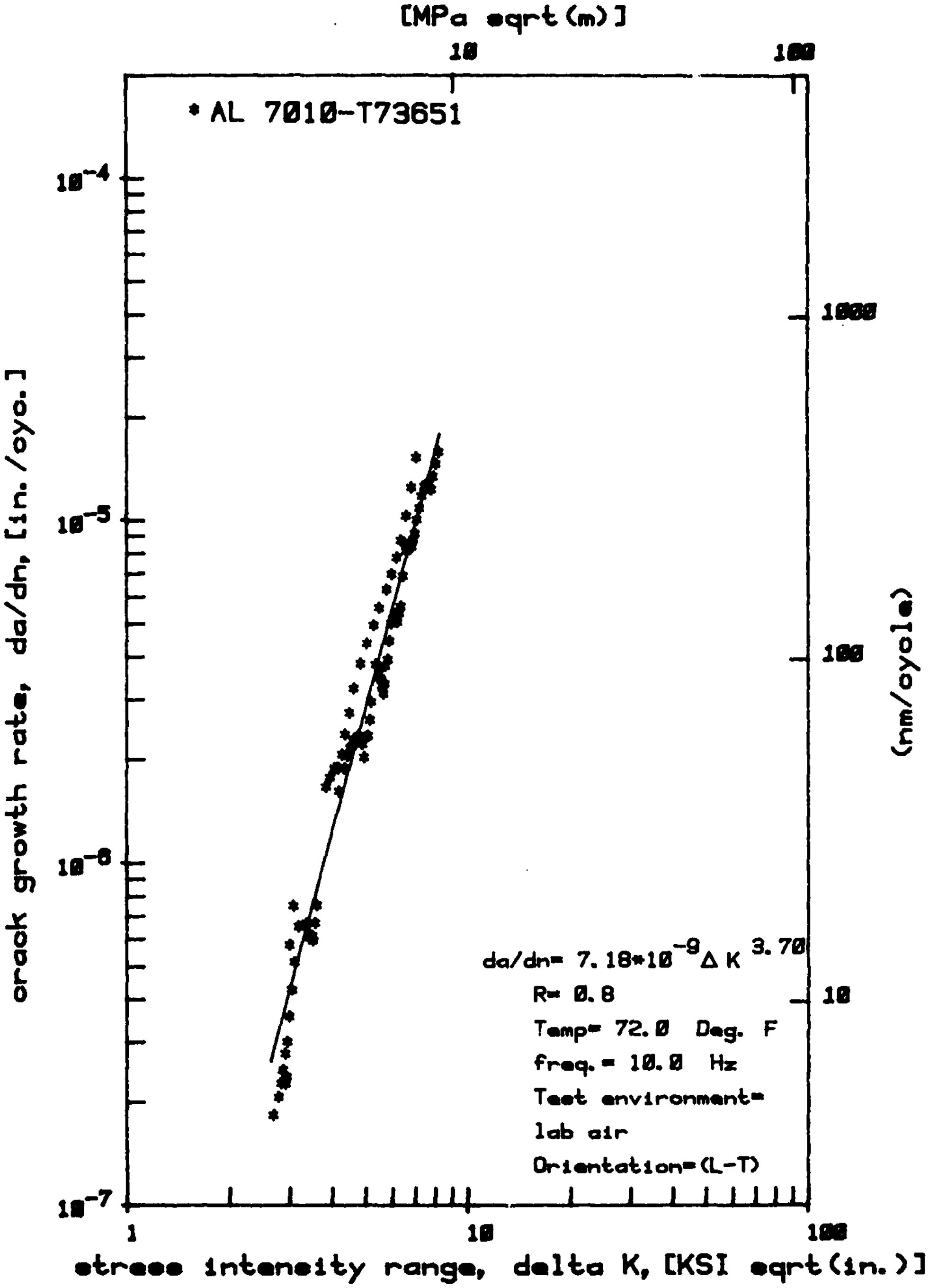


Figure 6. Room Temperature, Loading Ratio = 0.8 FCGR Test Data for Al 7010-T73651.

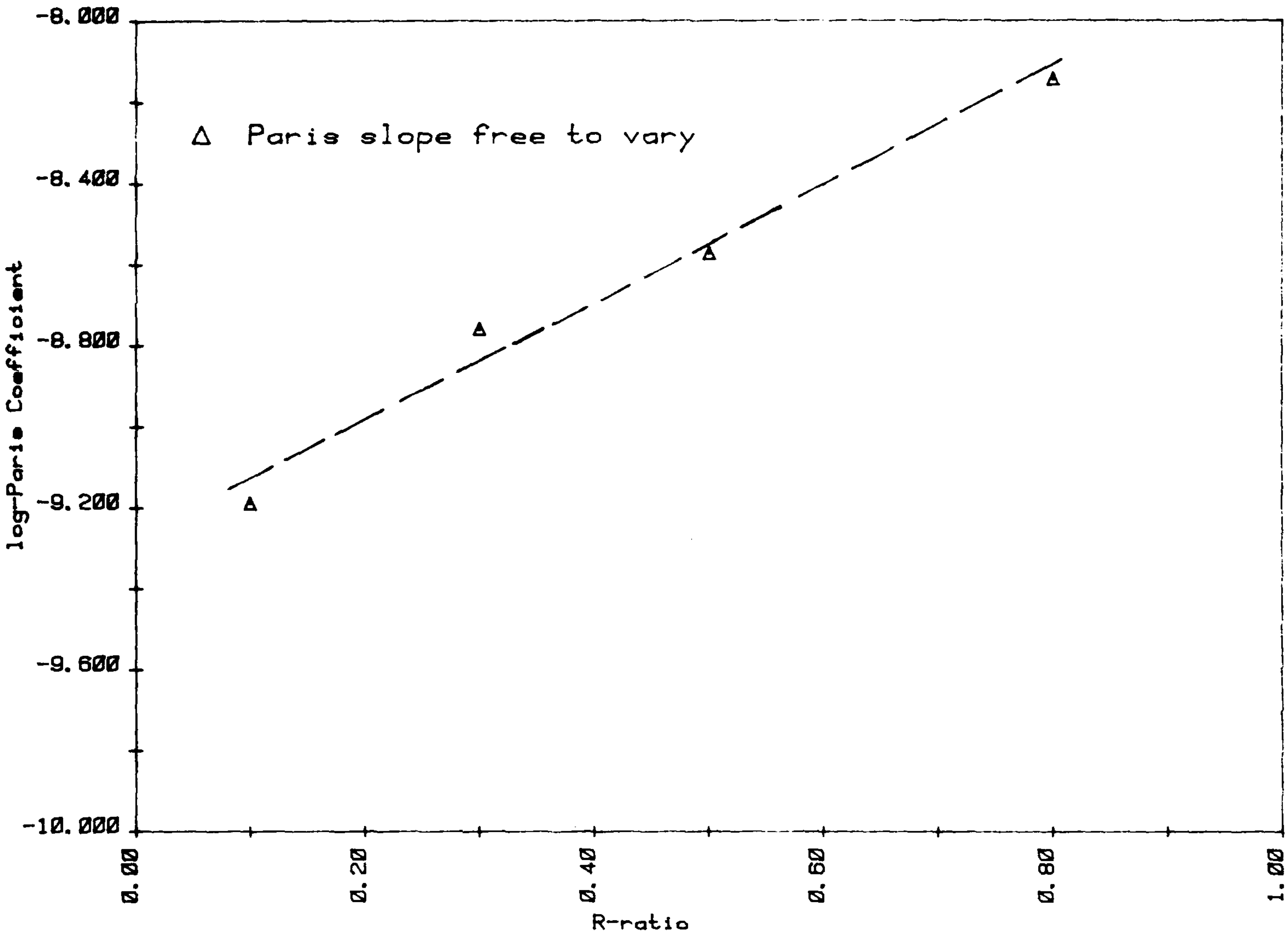


Figure 7. Loading Ratio, R, Versus Log-Paris Coefficient, Log C, for Al 7010-T73651 at 72°F (22°C).

The empirical equation just derived for the Paris coefficient as a function of loading ratio, equation (6), can now be substituted into equation (7),

$$\log da/dn = 1.438R - 9.277 + m \log \Delta K \qquad (8)$$

Again the Paris exponent, m, for the four best-fit straight lines corresponding to the four loading ratios under consideration are presented below.

PARIS EXPONENTS
[All Tests Conducted at 72°F (22°C)]

Loading Ratio, R	Paris Exponent, m
0.1	3.74
0.3	3.60
0.5	3.67
0.8	3.70

The average value, $\bar{m}$, is equal to 3.68. The maximum value among the four exponents is 3.74 and the minimum value is equal to 3.60, representing a range equal to $\pm$ 2 percent of the average value Paris exponent, $\bar{m}$. By substituting the average Paris exponent, $\bar{m} = 3.68$, into equation (8) and taking the antilogarithm of both sides of the resulting expression a generalized expression, equation (9) is derived:

$$\log da/dn = 1.438R - 9.277 + 3.68 \log \Delta K$$

$$da/dn \approx 10^{(1.438R-9.277)}\ \Delta K^{3.68} \qquad (9)$$

This expression for the test material aluminum alloy 7010-T73651 is applicable for a loading ratio range from 0.1 to 0.8 in a 72°F (22°C) laboratory air test environment.

The best-fit straight lines were then again determined for the same R-ratio data sets of stress intensity range and corresponding crack growth rate with the Paris exponent, m, fixed at the average value, $\bar{m}$ = 3.68, and only the Paris coefficient, C, free to vary. The four new equations (10 through 13) corresponding to the four loading ratios are as follows:

PARIS EQUATIONS
[All Tests Conducted at 72°F (22°C)]

Loading Ratio, R	Paris Equation	
0.1	$da/dn = 7.28 \times 10^{-10}\ \Delta K^{3.68}$	(10)
0.3	$da/dn = 1.47 \times 10^{-9}\ \Delta K^{3.68}$	(11)
0.5	$da/dn = 2.61 \times 10^{-9}\ \Delta K^{3.68}$	(12)
0.8	$da/dn = 7.31 \times 10^{-9}\ \Delta K^{3.68}$	(13)

The log-Paris coefficients for these four equations are plotted in Figure 8 (square symbol) along with the coefficients previously discussed (triangular symbol in Figure 7) that were calculated by letting both the coefficient and exponent freely vary in fitting a Paris straight line. This latter approach results in calculating Paris coefficients that plot with a much narrower scatter band. The best-fit straight line to these new Paris coefficients is:

$$\log C = 1.418R - 9.275 \qquad (14)$$

This equation is very close to equation (6). For the scale employed in Figure 8, visual detection of the two lines' separation occurs at a loading ratio approximately equal to 0.5 and they continue to separate at a shallow angle with increasing loading ratio.

Once again starting with equation (8) and using equation (14) and the average Paris slope, $\bar{m}$ = 3.68

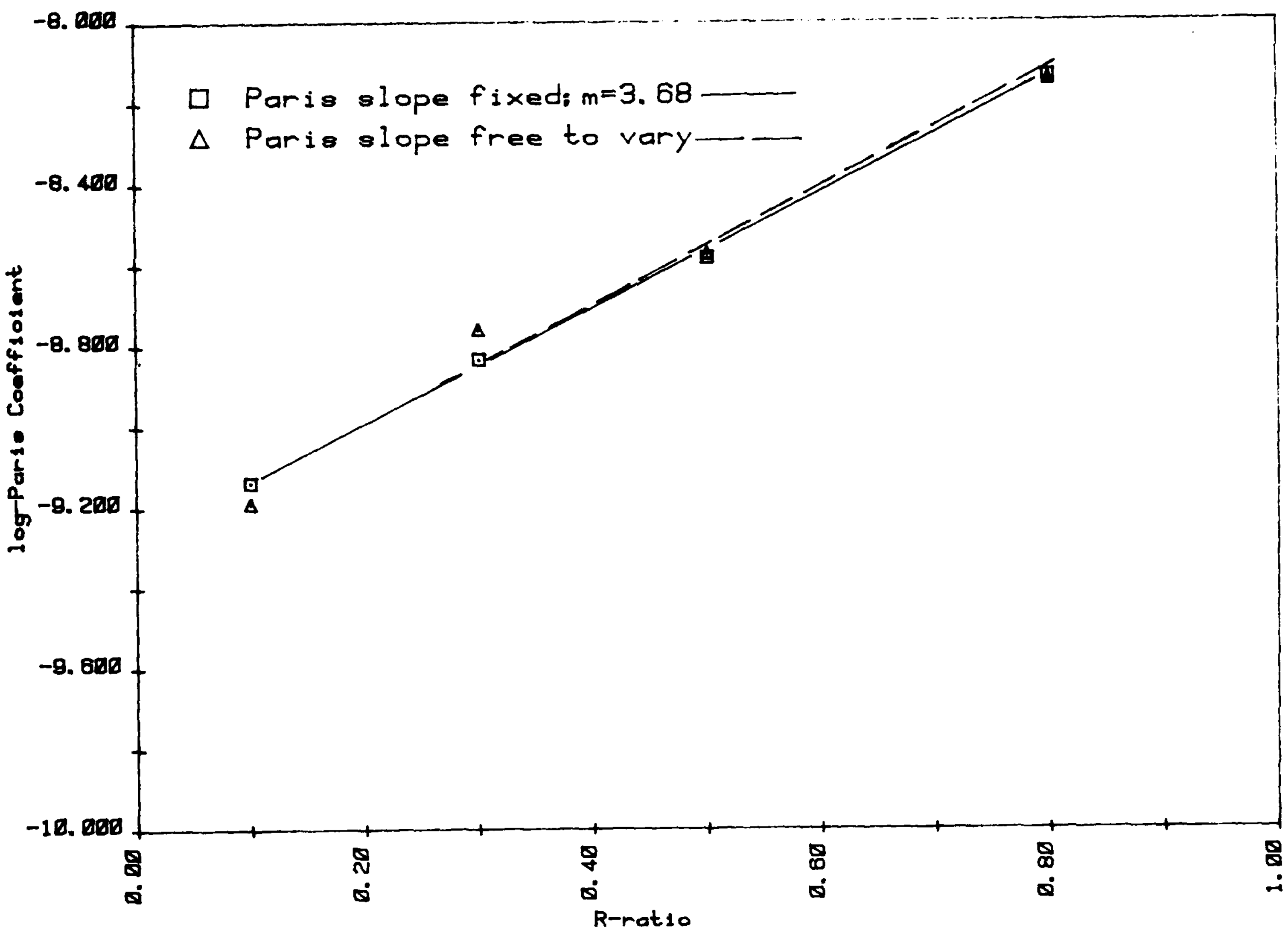


Figure 8. Loading-Ratio, R, Versus Log-Paris Coefficient, Log C, for Al 7010-T73651 at 72°F (22°C).

$$\log da/dn = \log C + m \log \Delta K \qquad (8)$$

$$\log C = 1.418R - 9.275 \qquad (14)$$

$$\log da/dn = (1.418R - 9.275) + 3.68 \log \Delta K$$

and then taking the anti-logarithm of both sides of this equation a second generalized expression, equation (15), can be derived

$$da/dn = 10^{(1.418R-9.275)} \Delta K^{3.68} \qquad (15)$$

This expression is quite close to equation (9) and for the test material also covers all loading ratios over the range from 0.10 to 0.80 in a 72°F (22°C) laboratory air test environment.

The largest gap in the R-ratio data sets was between the loading ratios equal to 0.5 and 0.8; a loading ratio in the middle of this gap, R = 0.65, was selected as a test case for the two generalized expressions, equations (9) and (15) the resulting predictions are equations (16) and (17).

$$da/dn = 10^{(1.438R-9.277)} \Delta K^{3.68} \qquad (9)$$

$$R = 0.65; \; da/dn = 4.547 \times 10^{-9} \Delta K^{3.68} \qquad (16)$$

$$da/dn = 10^{(1.418R-9.275)} \Delta K^{3.68} \qquad (15)$$

$$R = 0.65; \; da/dn = 4.436 \times 10^{-9} \Delta K^{3.68} \qquad (17)$$

When the lines corresponding to equations (16) and (17) are plotted on the axis scale used throughout this report the two lines appear indistinguishable. Therefore, it was concluded that the additional calculations of fitting the best-fit Paris equation with the exponent fixed equal to $\overline{m} = 3.68$ was superfluous for the test material and for the remainder of this discussion only equation (16) is used.

Two experimental approaches were taken to verify that the prediction, equation (16), would accurately represent data at the test-case an R-ratio equal to 0.65.

First, since the exponent $\bar{m}$ of the series of Paris equations has already been satisfactorily determined, to empirically establish a verifying equation with a set of data only the Paris coefficient need to be accurately determined experimentally. This curtails the necessity for generating a large range of data at an R-ratio of interest. Using this approach, two specimens were tested at a loading ratio equal to 0.65. To minimize test time an initially high stress intensity range received primary attention with the sole exception of one data point at a low stress intensity range that was established immediately following crack initiation of one of the specimens. The combined test results are presented in Figure 9. The line in Figure 9 represents the best-fit equation with the exponent fixed equal to $\bar{m}$ = 3.68. The equation that defines the line in Figure 9 is:

$$da/dn = 4.28 \times 10^{-9} \Delta K^{3.68} \qquad (18)$$

The lines representing the predictive equation (16) and the best-fit, fixed-exponent equation (18) to the actual test data are virtually indistinguishable.

Encouraged by this success an alternate approach was undertaken to verify the prediction equation (16). A third specimen was tested at a loading ratio equal to 0.65 but with an initial crack velocity of approximately 4×10^{-7} in./cycle (11.18 nm/cycle). The test results for this single specimen are presented in Figure 10. The solid line in Figure 10 represents the best-fit equation to this second data set which is:

$$da/dn = 4.09 \times 10^{-9} \Delta K^{3.65} \qquad (19)$$

and was calculated with both the Paris exponent and coefficient free to vary. The dashed line represents the predictive equation (16) which plots very close to and almost parallel to the solid line representing equation (19). The shift from the line representing the prediction, equation (16) to that line representing the best-fit equation to the data set, equation (19),

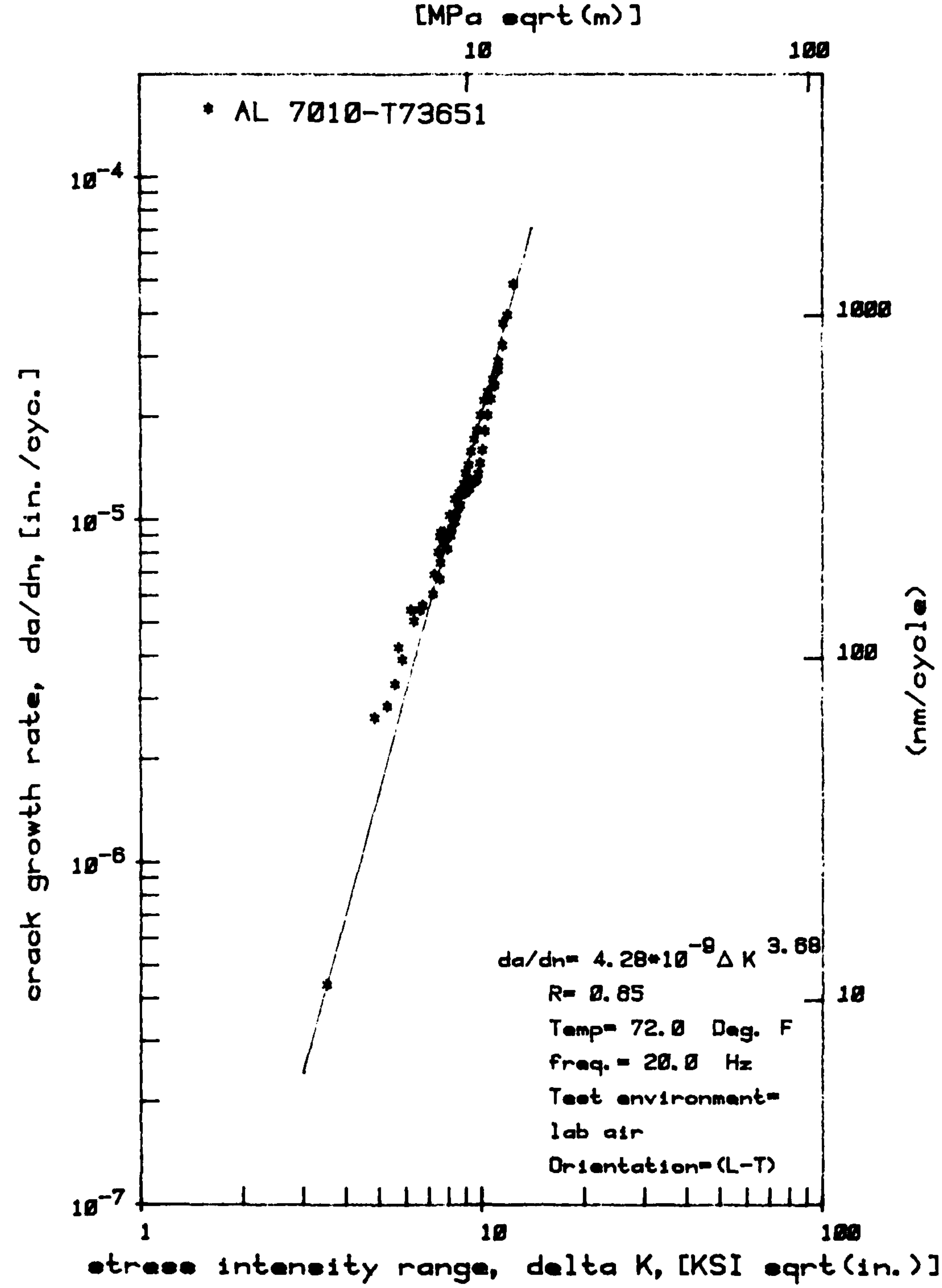


Figure 9. Fast Crack Growth Rate Region, Room Temperature, Loading Ratio = 0.65, FCGR Test Data for Al 7010-T73651.

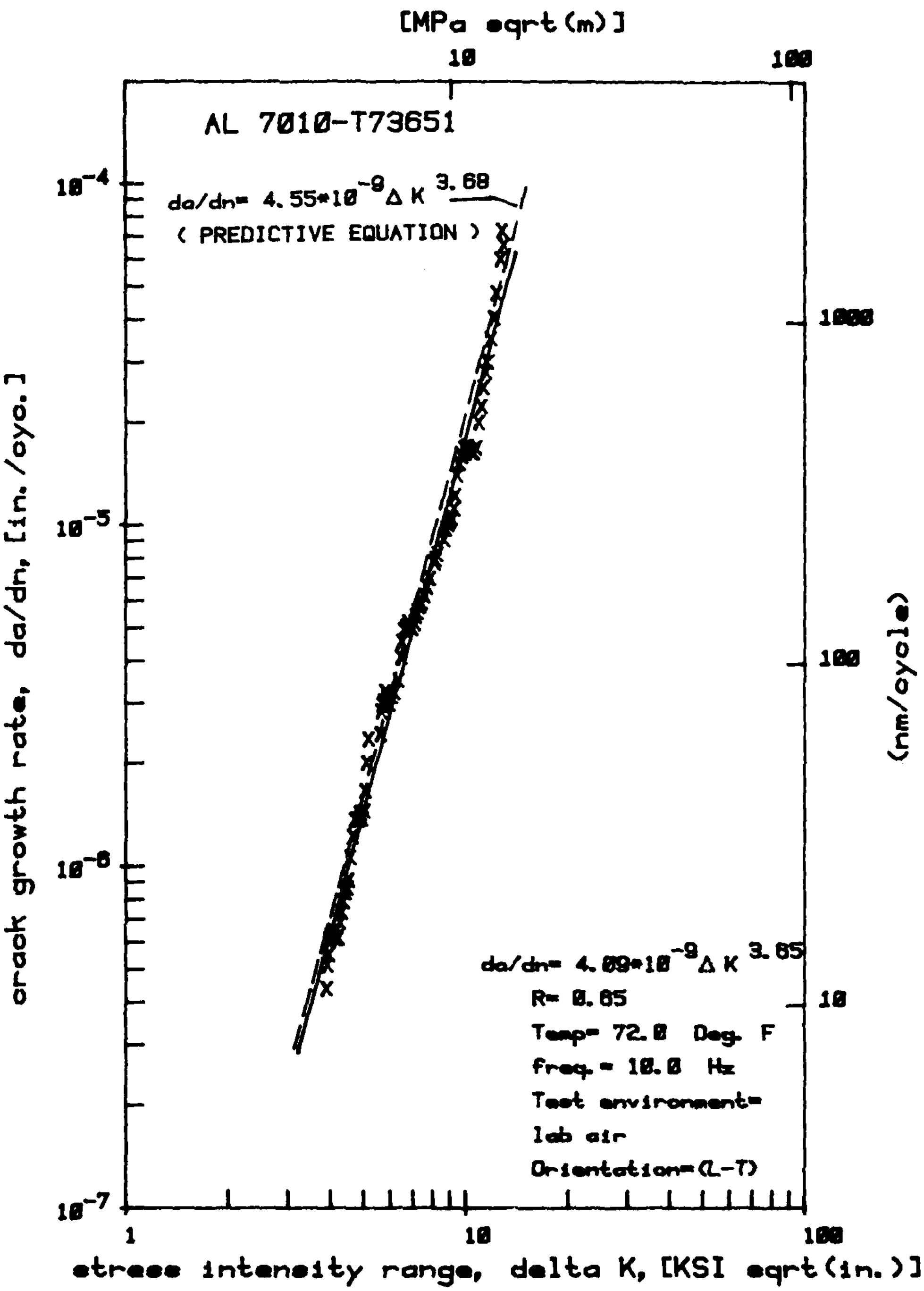


Figure 10. Full Velocity Range, Room Temperature, Loading Ratio = 0.65 FCGR Data for Al 7010-T73651.

is small when compared to the large shift from the best-fit line to the 0.5 R-ratio data set to that of the 0.8 R-ratio data set.

SECTION VI
CONCLUSIONS

1. For constant amplitude loading FCGR data for various positive loading ratios, the Paris coefficient for the linear region of the growth rate curve can satifactorily be modeled as a log-linear straight line relationship, i.e., R-ratio versus log-Paris coefficient.

2. The accuracy of the mathematical model was not significantly altered in recalculating the best-fit straight line to an R-ratio data set with the Paris exponent fixed equal to the average value of the individually calculated exponents, m, for the various R-ratio data sets. The extra calculations became unnecessary for the test material because the approach yielded a predictive Paris equation practically co-located with the prediction based on preliminary lines fitted with both the Paris exponent and coefficient free to vary.

REFERENCES

1. Hudson, C. Michael, "Effect of Stress Ratio on Fatigue-Crack Growth in 7075-T6 and 2024-T3 Aluminum Alloy Specimens," Langley Research Center, NASA Technical Note NASA TND-5390, August 1969.

2. Cervay, Russell R., "Mechanical Property Evaluation of Aluminum Alloy 7010-T73651, University of Dayton Research Institute, Technical Report AFWAL-TR-80-4094.